Potential of the deep UV broad bandwidth ArF driver for IFE
Recommendations for DOE sponsored IFE program

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National Ignition Facility (NIF) recently achieved a record inertial fusion yield 1.3 MJ with 1.9 MJ of laser energy (gain =0.7)

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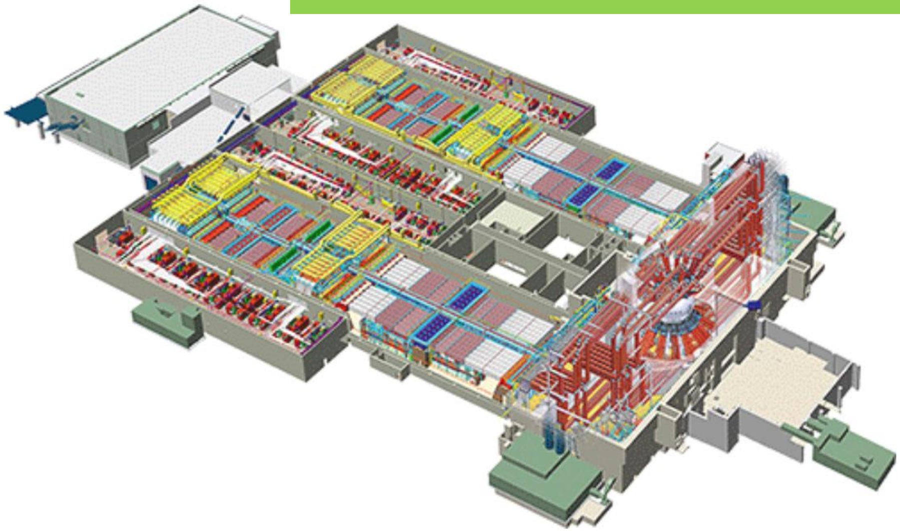
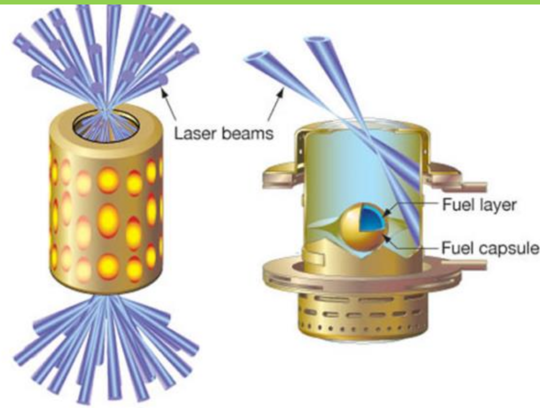
The NIF result demonstrated basic feasibility of inertial confinement fusion





Indirect Drive – laser light converted to x-rays that drive the implosion – approach chosen for NIF.

- The result is particularly impressive as the 1.3 MJ yield was achieved with only 230 kJ of x-rays absorbed by the capsule.

Direct laser drive is a much more efficient approach

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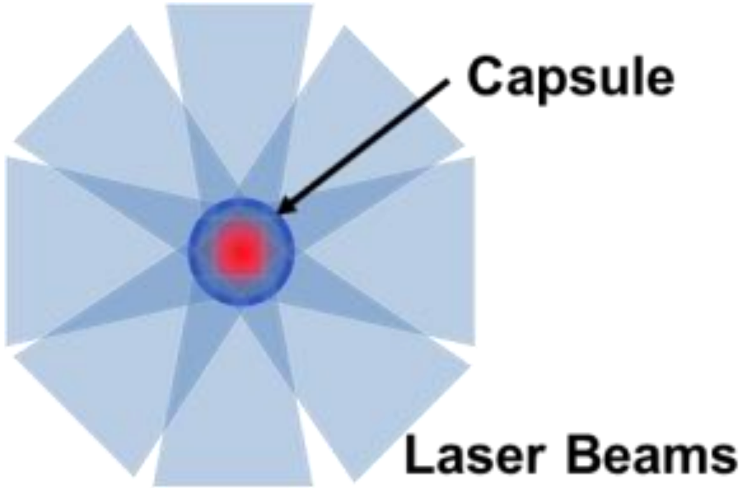
Direct Laser Drive – laser light directly illuminates the capsule



- Much more efficient than indirect drive (>6x)
- Potential to reach the high gains (100) required for the fusion energy application.

Best laser driver for high target performance

- Highly uniform target illumination
- Multi-THz bandwidth to suppress laser-plasma instabilities (LPI)
- Capable of zooming the focal diameter to follow imploding target
- Shorter laser wavelength to further suppress LPI and increase hydro-efficiency of implosion
- The 193 nm broad bandwidth ArF light meets all these criteria.

The NRL Electra electron-beam-pumped system is advancing the S&T of the high-energy ArF laser

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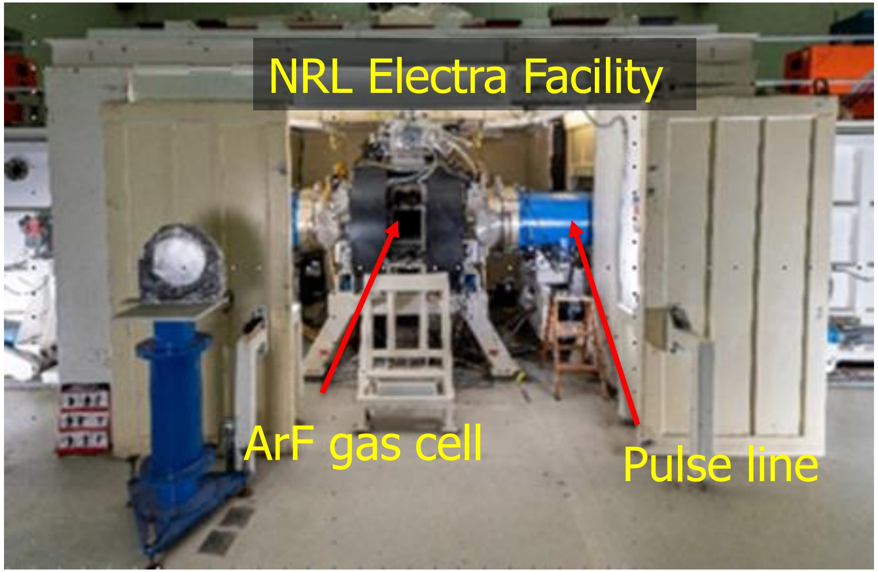

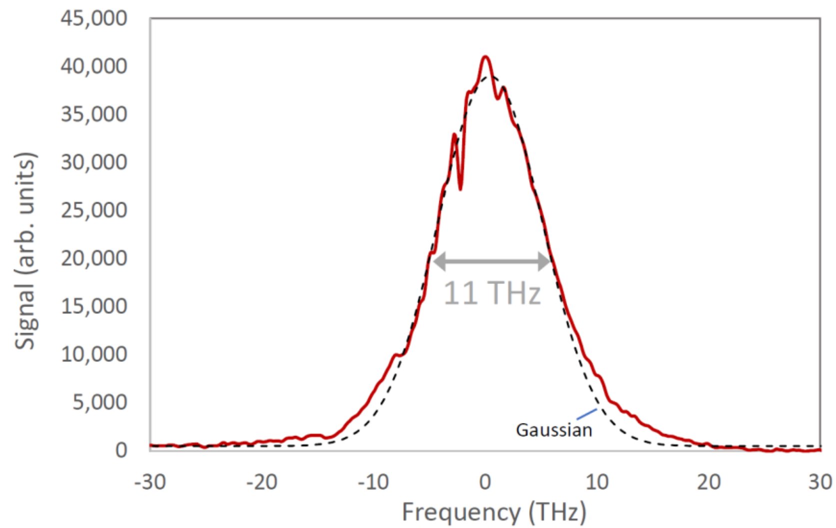

- Demonstrated 5 pulse per second operation with similar KrF operation
- Converted to ArF to advance basic electron-beam pumped ArF S&T
- World record ArF energy (200J)

- 11 THz FWHM bandwidth observed from Electra (single pass ASE output)
- Kinetic simulations predict indicate large ArF systems built for ICF/IFE can provide 10 THZ bandwidth light on target. See ref. 5

ArF use by lithographic industry has advanced durable 193 nm optics

Excimer angularly multiplexed laser optical systems can provide high target illumination uniformity and easy implementation of focal zooming

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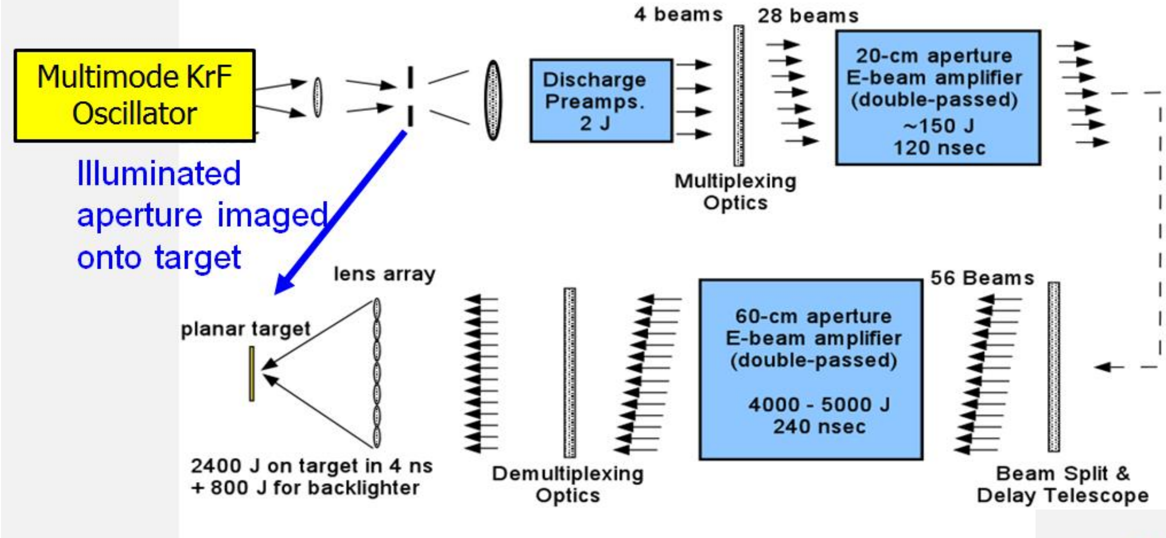
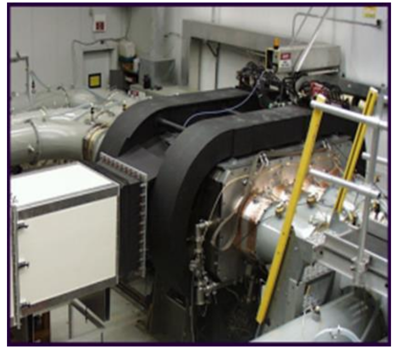
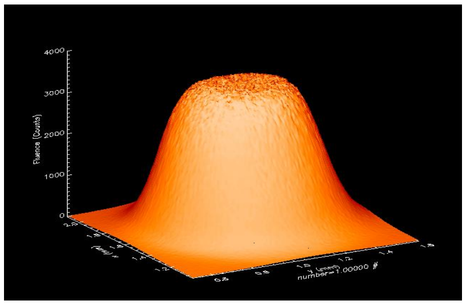
Nike: Aperture in the front end is imaged through the amplifier system to target

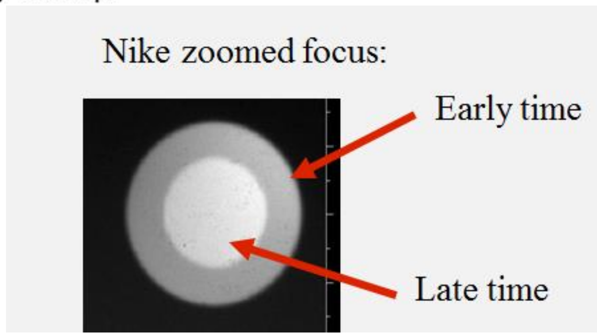


Nike 60-cm aperture 4-kJ amp



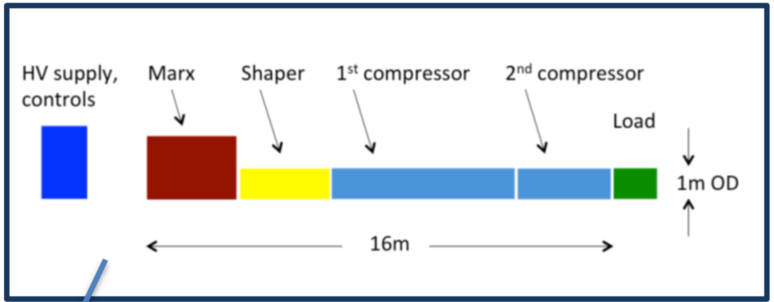


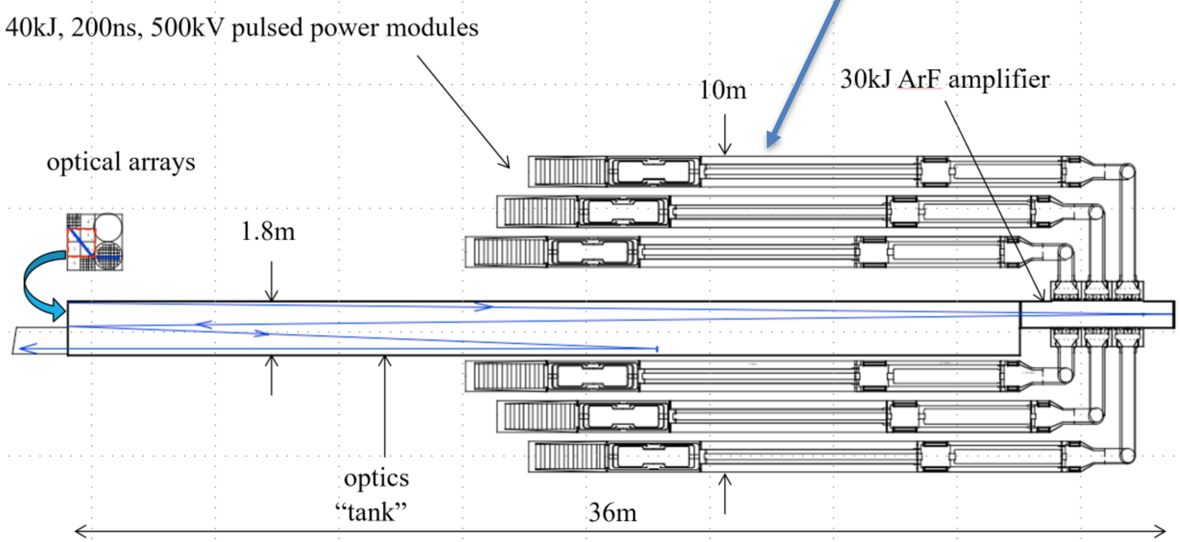
Time averaged laser spatial profile in target chamber



Path to high energy high-rep-rate ArF amplifier established

All solid-state switched (silicon & magnetic) pulse-power module
See white paper by M. McGeoch





ArF laser gas cell

M. McGeoch. Plex LTD

30-kJ 10-Hz 80-cm aperture ArF amplifier

LPSE* simulations of absorption fraction show advantage of using broad bandwidth 193 nm light vs current modest bandwidth 351 nm light

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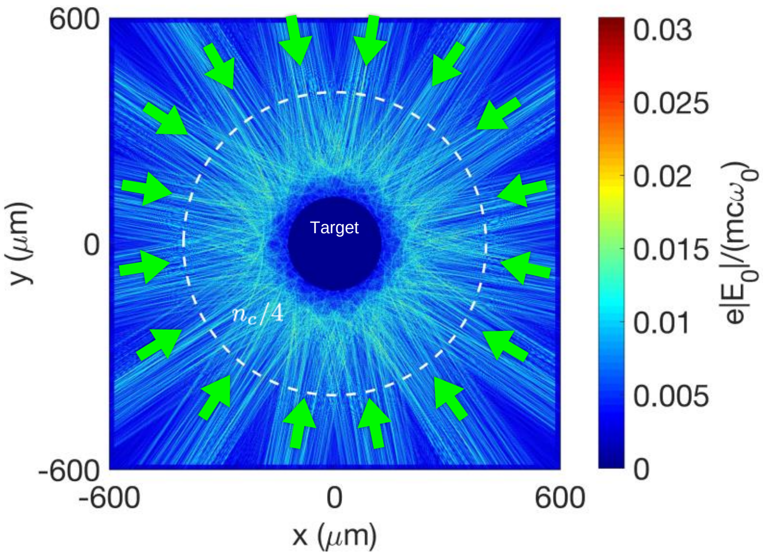

Laser Driver	wavelength	bandwidth	absorption
3rd-harmonic Nd:glass	351 nm	1 THZ	65%
KrF	248 nm	3 THz	86%
ArF	193 nm	5 THz	91%

Omega size pellet @ 5 x 10^{14} W/cm^2

- The ArF light is 91% absorbed versus 65% for the 1 THz 351 nm light mainly because the broader (5Thz) bandwidth suppresses cross beam energy transfer (CBET).
- Multi-THz bandwidth 351 nm light will be available on the LLE FLUX system to test code predictions

*Laser plasma simulation environment LLE developed LPI code

Hydrocode simulations show increased drive pressure and reduced risk from the two-plasmon decay instability with shorter laser wavelength

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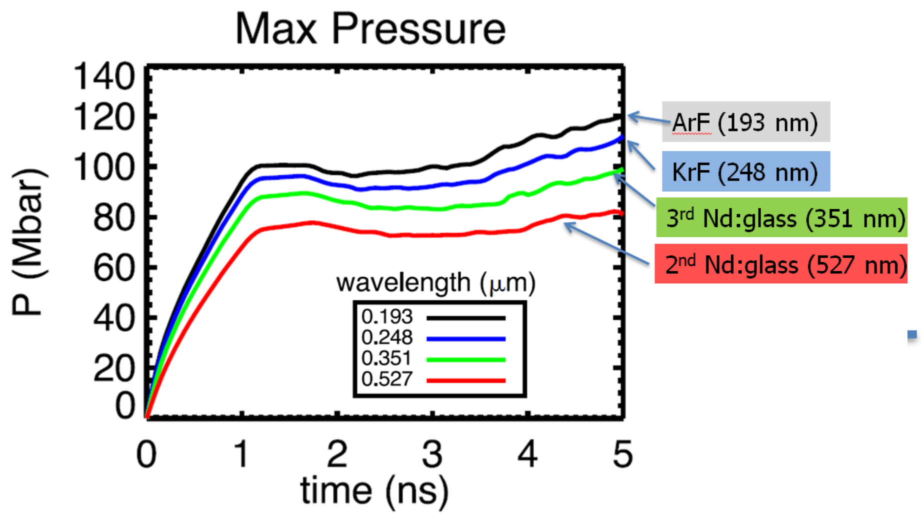
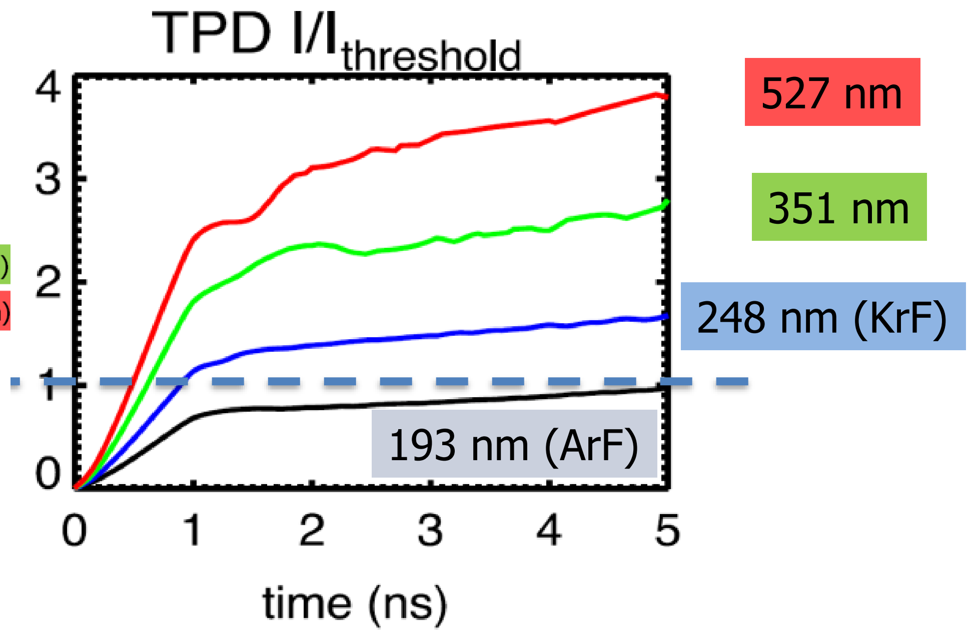
Ablation pressure vs laser λ from hydrocode
10^{15} W/cm^2 2.6 mm solid CH sphere



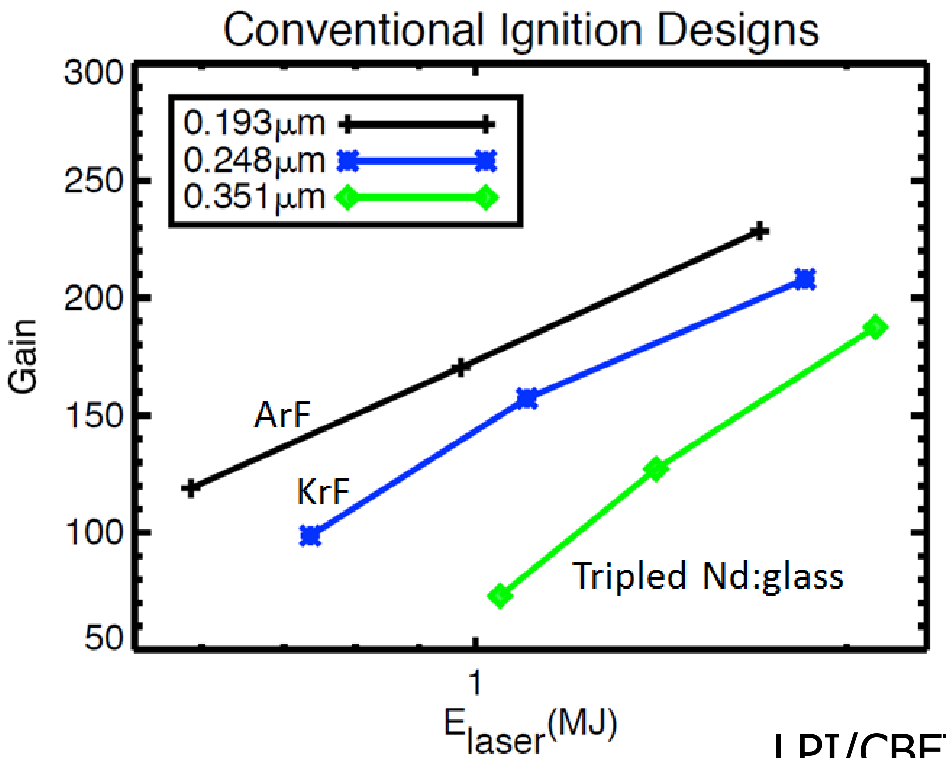
Direct drive ablation pressure increase's with shorter laser wavelength

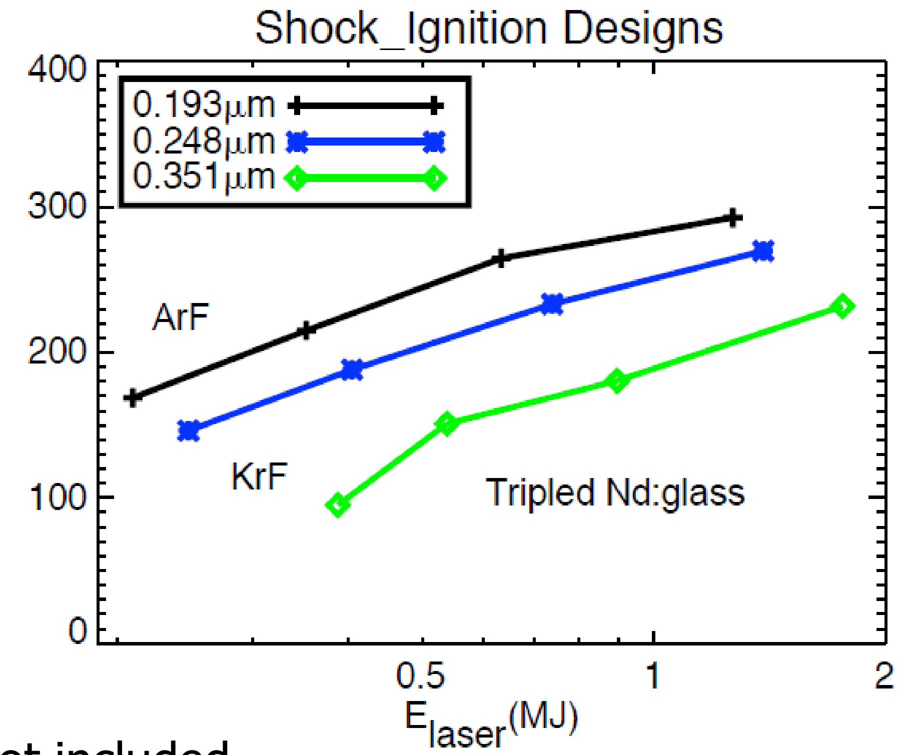
TPD thresholds vs laser λ from hydrocode
10^{15} W/cm^2 2.6 mm solid CH sphere



In this simulation one remains below the TBD threshold with 193 nm light

NRL FAST radiation hydrocode 1-dimensional simulations of the gain of conventional and shock ignition[1,2] direct-drive implosions for ArF, KrF and a tripled glass laser with zooming.





LPI/CBET not included

1.R. Betti, C.D. Zhou, K.S. Anderson, L.J. Perkins, W. Theobold, A.A. Solodov, Phys. Rev. Lett. 98 (2007) 155001.

2. *Simulations of high-gain shock-ignited inertial-confinement-fusion implosions using less than 1 MJ of direct KrF-laser energy*, Jason W. Bates, Andrew J. Schmitt , David E. Fyfe , Steve P. Obenschain , Steve T. Zalesak, High Energy Density Physics 6 (2010) 128–134

NRL 2D simulations indicate an ArF laser can achieve target gains (>100) needed for laser fusion power plant with much less laser energy than achieved by NIF

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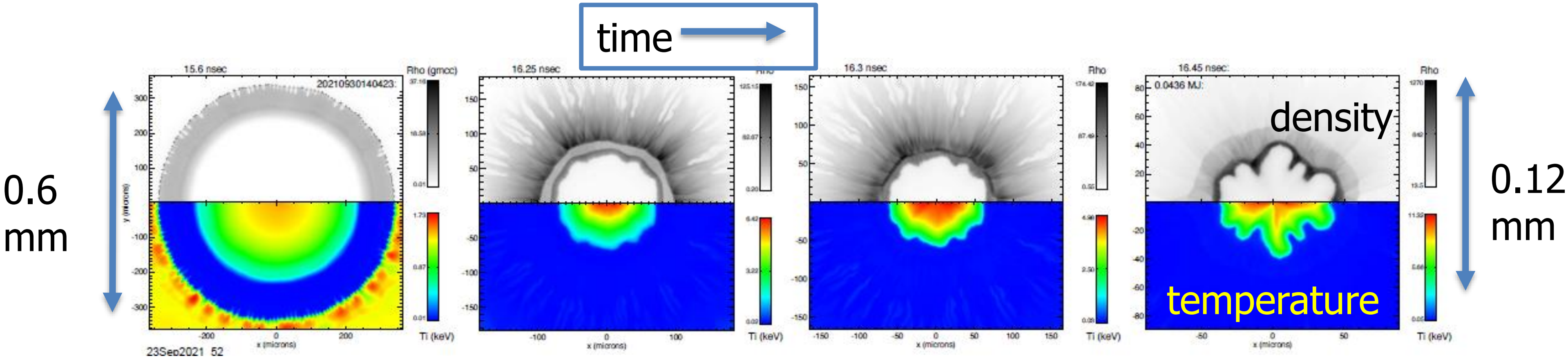
Sample NRL 2D simulation of a **410 kJ ArF** driven shock ignited implosion

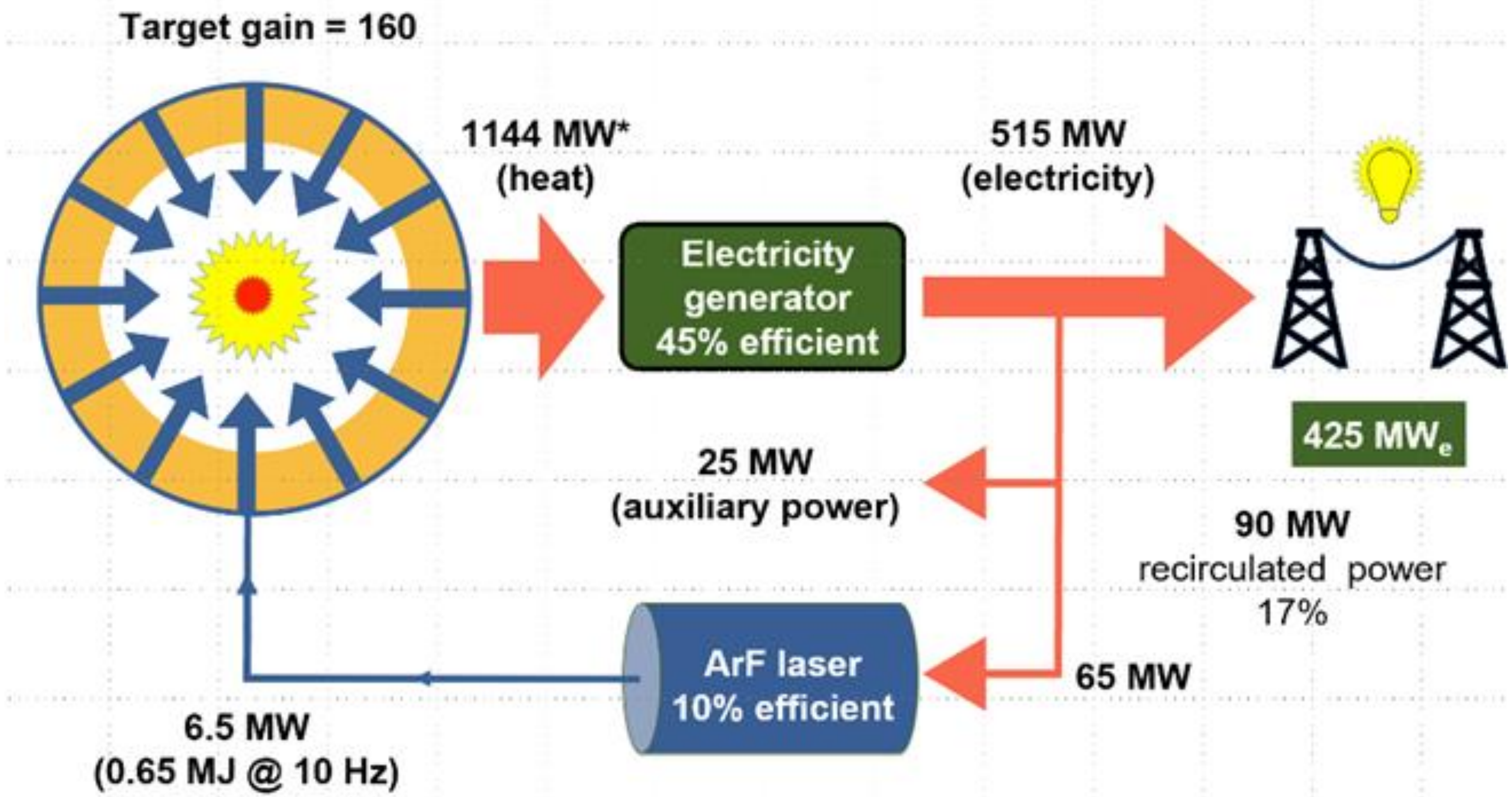


- 160x gain including effects of target imperfections
- 148x gain adding effects of laser imprint @ 5 THz bandwidth

A. Schmitt DPP 2021

Power flow in 425 MWe ArF power plant

0.65 MJ ArF laser operating @ 10 pulses/sec.



Phased plan progress from present to a pilot ArF laser fusion power plant

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Basic ArF laser IFE enabling S&T

- ArF physics: wide bandwidth (10 THz) & high intrinsic efficiency (16%)
- Path to high rep rate (10 Hz) and high (10%) wall plug efficiency identified
- 2D & 3D high gain (>100) implosion & LPI simulations

Phase I

ArF target physics

- Build 30 kJ ArF beamline (10 shots/hour)
- Planar LPI/hydro exp. @ 30 kJ

Power plant tech

- Advance high rep (10 shots/sec) laser tech
- Identify other critical tech for power plant

Phase II

High gain implosions

- Build ArF 700 kJ implosion facility. >100 shots/day
- DEMO robust gain >100

Power plant tech

- Build 30 kJ high rep rate (10 shots/sec) ArF beamline
- Develop all tech needed for power plant

Phase III

Pilot 650 kJ ArF laser fusion power plant

- Complete design & build
- Test components & procedures.
- Generate power (~400 MW_e)

The ArF laser could enable power plants with laser energy below 1 MJ, which would speed development time and reduce cost.

Recommend that New IFE program advance essential technologies building on advances in the HAPL program

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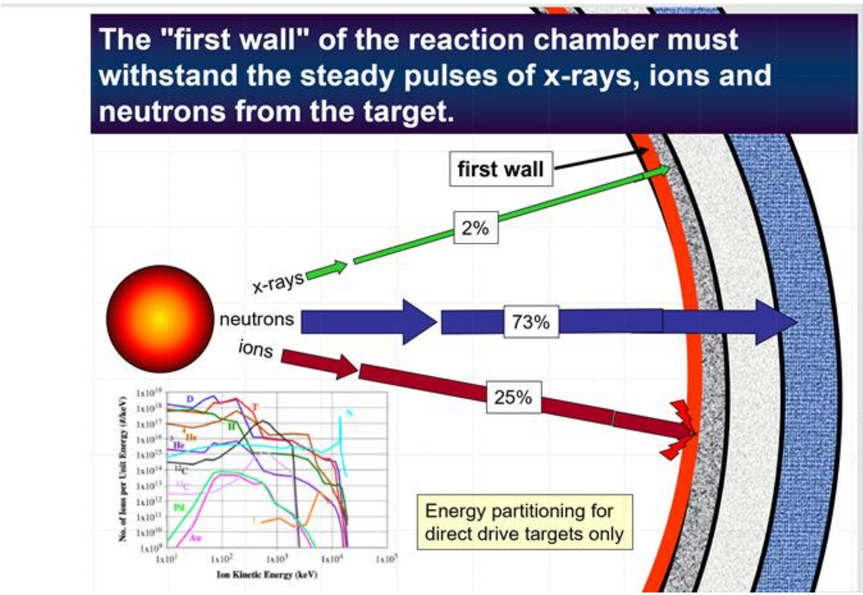
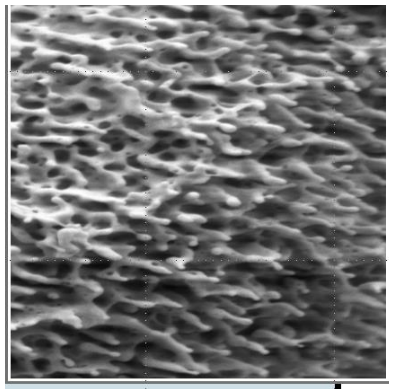
- Low cost target production – GA study provide cost estimate of $0.17 each
- Target injection & engagement
- Long lived first wall – strategies to avoid rapid damage from alphas
- Final optics –GIMMS & neutron damage resistant dielectric coatings developed & tested



Tungsten overcoat can withstand heat pulse but alphas imbed near surface and accumulated He pressure damages coating



Potential solution: foam tungsten overcoat that releases the He

Sam Zenobia (Wisconsin)

IFE path forward

- There is now greater need than ever for alternate environmentally friendly & affordable energy sources that can be deployed in a relevant time frame.
- IFE could turn out to be the fastest route to practical fusion energy.
- The new IFE effort needs to be open to new credible technologies & approaches to achieve its goals -- while being mindful of the challenges.

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